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An evaluation of transported pollution and respiratory–related hospital admissions in the state of New York

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ABSTRACT

Human exposure to air pollution transported from the Midwest is evaluated in eight New York State (NYS) regions over ten summers (1997 – 2006) for association with respiratory–related hospital admissions. Days when pollution is transported into the Northeastern United States (U.S.) were identified by using back–trajectories from the eight regions. These back–trajectories help identify predominant meteorological patterns associated with "polluted" air parcels (originating in the Midwest where power plant emissions are known to be relatively high) and "clean" air parcels (originating from the North where pollution is known to be relatively low). Ambient ozone concentrations measurements were used to validate the classification of "polluted" and "clean" air parcels. These classifications were then used to define the days of high– versus low–exposure for populations residing within each region. The results of this analysis indicate that the risk of being hospitalized for respiratory–related illness in NYS is greater on those days when air is transported from the Midwest as compared to days when air is transported from the North. Using a refined method to examine air parcels moving through a boundary drawn around high–emitting power plants in the Midwestern U.S. resulted in stronger associations across more regions (significant odds ratios ranging from 1.06 to 1.16 for the entire study time period for six of the eight NYS regions). An assessment of temperature and its impact on the odds ratio calculation in the New York City metropolitan region indicates that temperature alone does not explain the increased association between air pollution and respiratory–related hospital admissions.

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1. Introduction

The Clean Air Act (CAA) requires that the United States (U.S.) Environmental Protection Agency (EPA) set National Ambient Air Quality Standards (NAAQS) for pollutants considered harmful to human health and the environment. Previous research has shown that high ambient ozone levels have harmful effects on humans (Burnett et al., 2001; Medina–Ramon et al., 2006; Tolbert et al., 2007; Lin et al., 2008; Moore et al., 2008). The formation and distribution of ozone is driven by chemical interactions involving nitrogen oxides (NO_X) and volatile organic compounds (VOCs) in the presence of sunlight, as well as prevailing meteorological conditions. These pollutants and their precursors can be transported downwind, contributing to pollutant levels at locations much farther from the emission sources, potentially impacting human health in downwind areas.

The Ozone Transport Assessment Group (OTAG) conducted a two–year regional assessment of ozone transport (OTAG, 1997) and concluded that the central portion of the 37–state OTAG domain (Figure 1) was characterized by persistent elevated ozone levels producing an "ozone pool". High ozone levels in the southern portion of the OTAG domain were associated with near–stagnant pollutant conditions whereas high ozone levels in the northern portion of the OTAG domain were associated with fast–moving weather systems and persistent transport conditions from inside the OTAG domain–particularly in the Midwestern U.S. where major NO_X emitting power plants are located (OTAG, 1997; Rao et al., 1997).

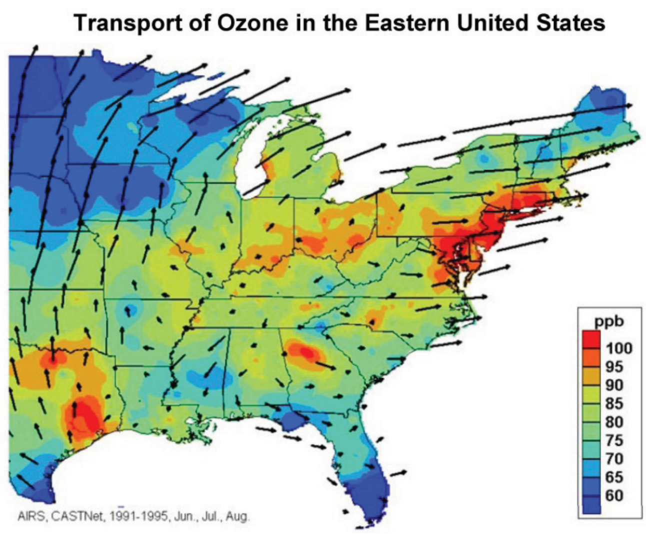

Figure 1. *Transport of ozone and precursor chemicals from Midwestern U.S. into Northeastern U.S. (Source: OTAG, 1997).*

Since the issuance of the OTAG Report, the implementation of the NO_X Budget Trading Program (fully implemented in 2004) has significantly reduced NO_X emissions from the power–generating sector in the Midwest (U.S. EPA, 2005; Gego et al., 2007). In its most recent evaluation of the nation's air quality, the U.S. EPA found that the maximum 8–h daily average ozone concentrations in the Eastern U.S. have declined by 10 percent since 2001 (U.S. EPA, 2010). While the predominant source of NO_X emissions is now from on–road vehicles (36%), the power industry still accounts for 23% of the total emitted NO_X in the Northeastern U.S. (U.S. EPA, 2005). Distinguishing transported pollution from locally emitted pollution is critical in improving our understanding of the health outcomes resulting from regulatory actions.

Previous studies have examined the transport of polluted air parcels from the Midwest into the Northeastern U.S. Ryan et al. (1998) used various monitoring data and back–trajectory analysis to examine the meteorology, chemistry and source of a severe regional ozone event during July 12–15, 1995 over the Baltimore–Washington region. They found that the chemical composition aloft (high ozone, sulfur dioxide and total reactive nitrogen and very low nitric oxide concentrations) indicated photochemical aging of an air parcel transported some distance with, at least partially, a coal combustion source. Brankov et al. (1998) examined the role of synoptic–scale weather patterns in pollution transport and its influence on observed ozone concentrations at three locations in NYS, New Jersey, and Massachusetts. They found that consistently high ozone levels in the Northeast tend to occur when air arriving at the monitoring sites has previously traveled over the Southeast and Midwest.

Taubman et al. (2004) used airborne observations of trace gases, particle size distributions and particle optical properties taken from New Hampshire to Maryland during a multi–day ozone–haze episode on August 14, 2002 and found that backward trajectories indicated source regions in the Midwest and Mid–Atlantic urban corridor. In a separate study, Taubman et al. (2006) used cluster analysis of back–trajectories in conjunction with vertical profile data to identify the source regions and characterize transport patterns during summertime pollution episodes. The largest number of trajectories for these high–pollutant events lay over the northern Ohio River Valley. The resulting chemical composition of the air masses (high ozone values, large SO_2/CO ratios, highly scattering particles and large aerosol optical depths) supported this conclusion. Rainham et al. (2005) assessed whether meteorological conditions modified the relationship between short–term (daily) exposure to particulate matter and mortality using a hybrid spatial synoptic classification system. The authors found that although there does not appear to be any systematic patterning of modification, variation in pollutant concentrations seems dependent on the type of synoptic category present.

This study used two approaches to successively classify the transport of polluted air parcels for ten consecutive summer seasons (June, July and August) between 1997 and 2006. The objective of the study was to determine if air parcels transported from the Midwest into NYS lead to differentiable ozone concentrations and, if so, whether or not these transported air parcels were also associated with distinguishable daily respiratory–related hospital admissions. The study complements previous studies in two ways; first, it presents a methodology for identifying polluted air parcels versus relatively clean air parcels, and second, it uses these air parcel classifications to identify exposed and unexposed groups within eight NYS regions for purposes of evaluating the prevalence of respiratory–related hospital admissions between the two groups.

2. Air Quality and Health Data

The daily maximum 8–h averaged ozone concentrations for June 1 through August 31 for the years 1997 through 2006 were calculated from the hourly measurements archived at the U.S. EPA's Air Quality System (AQS) database (http://www.epa.gov/oar/data/aqsdb.html) and Clean Air Status and Trends Network (CASTNET) (http://www.epa.gov/castnet/). The locations of the monitors used in the study are shown in Figure 2. The daily maximum 8–h ozone concentrations were calculated by applying an 8–h moving window to the hourly time series and selecting the 8–h time window with the highest averaged ozone concentration value. Only those days having greater than 20 hours of data were used for computing the daily maximum.

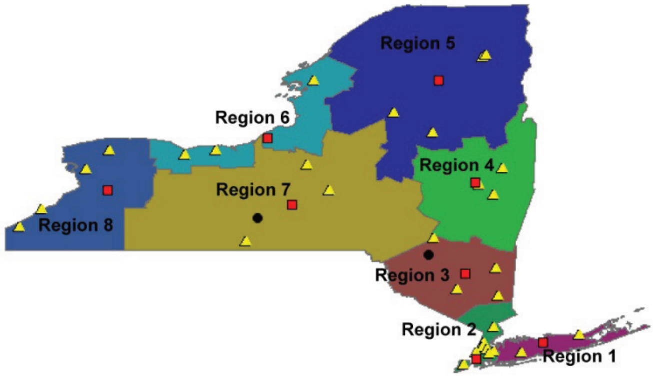

Figure 2. *Location of eight NYS regions, back-trajectory origination sites (red squares), CASTNet monitoring sites (black circles) and AQS monitoring sites (yellow triangles).*

Hospital admission information was obtained from the NYS Department of Health Statewide Planning & Research Cooperative (SPARCS), which collects inpatient information for all NYS hospitals, excluding psychiatric and federal hospitals. SPARCS is a legislatively mandated discharge database that is known to include at least 95% of acute care hospitalizations. Respiratory diseases were based on the International Classification of Diseases, 9th Revision (ICD–9 code; US Department of Health and Human Services, 1991), and included: asthma (ICD–9 code 493), chronic bronchitis (491), emphysema (492), and chronic obstructive pulmonary disease (COPD; 496).

3. Air Pollution Transport

This study involved the successive classification of transport directions into a limited number of relevant categories to target air parcels transported from the Midwest into NYS. The method implements various statistical and epidemiological techniques to examine the differences in ambient ozone concentrations and daily respiratory–related hospital admissions in correspondence with the selected transport categories.

The calculation of the transport direction was performed with the Hybrid Single–Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Draxler and Hess, 1997). HYSPLIT was set to calculate back trajectories, i.e., to perform the calculation back in time to determine the origin of the transported air parcel. The model was run repetitively to simulate transport every day during the 10 summers considered (total of 920 days). In addition, eight starting locations approximately coinciding with the center of the eight regions in NYS (http://www.dec.ny.gov/chemical/34985.html) were utilized for each simulated day. A total of 7 360 trajectories (920 days x 8 starting locations) were examined, however, eight days on average for each region were eliminated from further interpretation because simulations ended prematurely (less than 48 hours simulated) due to missing meteorological data.

For all simulations, the starting elevation for the trajectory was fixed at 500 m above ground level to reproduce transport across the Appalachian Mountains in the atmospheric residual layer aloft at night, yet to represent surface–level ozone concentrations through vertical mixing during the day. Vertical motion was reproduced using the vertical velocity fields that are produced by the meteorological model rather than the more restrictive isentropic or isobaric displacement options also available to simulate transport. Initial time was set in the afternoon (1800 UTC) to correspond to peak ozone times when pollutants are mixed uniformly throughout the daytime atmospheric boundary layer (Ryan et al., 1998; Rao et al., 2003). Simulated time was set to 48 hours to allow enough time to capture regional transport patterns, but minimize errors that accumulate with the length of simulation (Stohl and Seibert, 1998; Taubman et al., 2006). The meteorology fields used to run HYSPLIT included hourly pressure, vertical height, wind speed and wind direction. These data were obtained from the North American Regional Reanalysis (NARR) dataset (http://nomads.ncdc.noaa.gov/data.php#narr_datasets).

3.1. Classification of transport directions

It is well known that air flow directions vary continuously in time and space, covering the entire 360 degree spectrum about each starting location. Yet, numerous statistical methods require all data to be classified into a limited number of categories (the major transport directions) prior to being processed. Deciding on the number of categories to form as well as setting their limits contains some subjectivity. Two options were used to perform this task. The first option, hereafter referred to as the *arc* method, relies on the calculation of the azimuth; the angle measured from 0 degrees of the starting trajectory point to its endpoint location 48 hours back in time.

Five major directions (Figure 3) were identified with this method. The northerly direction was more broadly defined as one group because ozone concentration levels transported from the north (over Canada) are, in general, low. Higher (but more variable) ozone concentration levels are associated with transported air masses from the westerly, southwesterly, and southerly directions, making it important to further delineate these wind patterns in defining exposure to pollution–particularly since this study seeks to investigate exposure from transported pollution from power plant emissions in the Midwest (Brankov et al., 1998; Ryan et al., 1998; Taubman et al., 2004; Taubman et al., 2006). In general, the westerly arc class isolated emissions from major industries across the Great Lakes, the southwesterly arc class targeted major power plant emissions in the Midwest, and the southerly arc class targeted predominantly mobile source emissions transported north along the Eastern seaboard transport corridor. There was no particular rationale for defining the southeasterly arc except that it was the remaining arc after classifying the other critical directions.

The second classification method refines the methodology described above to further isolate transported pollution from the Midwest. It relies on the definitions of two longitude–latitude bounded zones representing high power plant emissions in the Midwest and relatively cleaner air originating in the North (Figure 4). A given day is said to correspond to transport from the Midwest if the trajectory calculated for that day enters the bounded zone at any time during the 48–h trajectory simulation. Note that the arc method investigates directions calculated after 48–h exactly (and not continuously). The two options will not lead to completely independent results as each zone is part of a single broader arc classification. However, the zone and arc classifications will not lead to the same results for every simulated day. Slow moving air masses may fit the arc method requirement to be classified in a given class but may not be included in the matching zone classification because they did not reach back, far enough to enter the zone limits. Conversely, a trajectory that curves during the 48 simulated hours may not be included in a given transport class as defined by the arc method but may enter the matching zone boundaries later on during the 48–h simulated period.

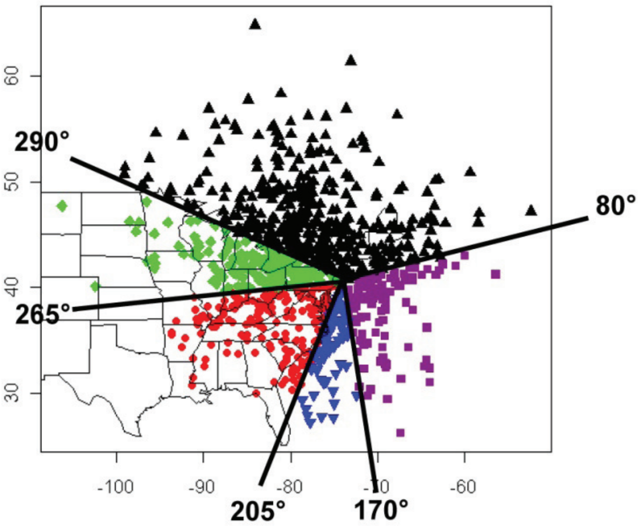

Figure 3. *Arc approach. Black triangles pointing up represent the direction of end-points for back-trajectories originating from the North, purple squares represent the southeasterly direction of origin, blue triangles pointing down represent the southerly direction of origin, red circles represent the southwesterly direction of origin, and green diamonds represent the westerly direction of origin. X-axis is longitude, y-axis is latitude.*

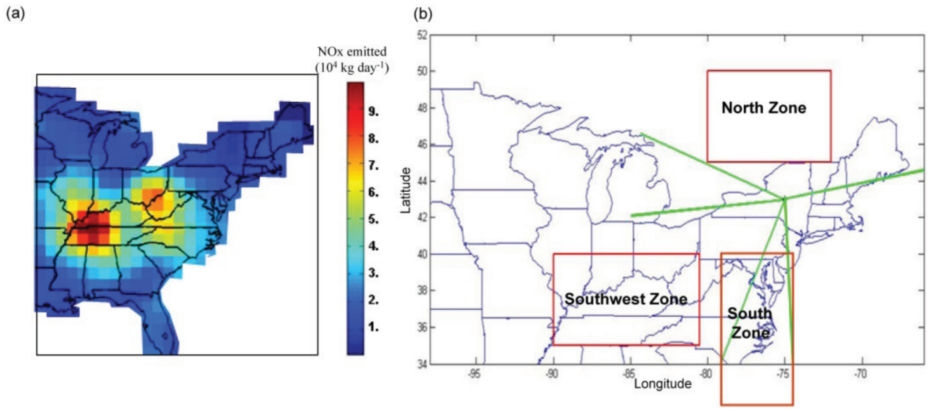

Figure 4. *Bounded zone approach. Panel* ***(a)*** *shows high NO_X emissions (July 1997 shown as an example) originating from power plants in the Midwestern U.S.;* ***(b)*** *shows boundaries drawn for identifying days when the air parcel passed through a zone in the Midwest versus days it passed through a zone in the North (red rectangles). Also shown is the southern zone used in the temperature analysis.*

For this study, using the two successive approaches to define the origin of the polluted air parcel was important because it allowed us to examine the levels of pollution transported from all directions using the arc method first, before applying the more targeted bounded zone method. While the boundaries for the zone approach were established a priori, this first evaluation was necessary to substantiate that relatively polluted air was transported into NYS from the southwest as opposed to other directions.

3.2. Assessment of corresponding ozone concentrations and pollutant transport directions

Daily maximum 8–h ozone concentrations were averaged for each region and matched to their respective air transport direction for each day for each of the eight NYS regions. For the arc method, the mean ozone concentrations for those days classified as southeasterly, southerly, southwesterly or westerly were compared to the mean ozone concentration for those days classified as northerly using the two–tailed t–test with a 95% confidence level. The same analysis was repeated for the zone method except that only those days classified as passing through the southwesterly zone versus the northerly zone were used. The purpose of this examination was to identify polluted air parcels (relative to the cleaner air parcels from the North) and to substantiate that air parcels from the Midwest represented relatively higher ozone for determining days of exposure for assessing associations with respiratory–related hospital admissions.

3.3. Assessment of hospital admissions and transport directions

Daily respiratory–related hospital admissions were summed for each region and matched to their respective air parcel direction for each day for each of the eight NYS regions. The daily respiratory–related hospital admissions associated with air parcels originating from the Midwest and the North were used to define the exposed and unexposed groups, respectively, for calculating an unadjusted odds ratio. An odds ratio calculation indicates the odds of an event occurring in the exposed group relative to the odds of it occurring in the unexposed group (Rothman, 2002). "Unadjusted" odds ratio indicates that the calculation does not adjust for other variables that may impact the results (see Section 5). For this study, the calculation estimates the odds that a respiratory–related hospital admission will occur on days when air is transported from the southwest relative to the odds of it occurring on days when air is transported from the north. An odds ratio greater than 1.0 indicates that hospital admissions are more likely to occur on days when the air parcel originates from the southwest, and an odds ratio of less than 1.0 indicates that hospital admissions are less likely to occur on days when the air parcel originates from the southwest. The 95% confidence interval (95% CI) was also used to describe the precision of each odds ratio.

While the unit of comparison was daily, the odds ratio was calculated for all days (total number of days that polluted air was transported into the region versus the total number of days that relatively clean air was transported into the NYS region). Since the number of exposed days varied from the number of unexposed days, the summed hospital admissions for each group were normalized by the total number of days.

3.4. Examination of temperature

The effect of temperature was further investigated for region 2 by defining days of high exposure using two different bounded zone classes (southwesterly and southerly), both of which had relatively high temperatures, and then comparing the odds ratios for these two groups. The intent of this analysis was to determine whether temperature, rather than pollution or some other factor, could be responsible for an odds ratio greater than 1.0. The boundaries for the southerly zone were drawn to represent the relatively longer–range transport from the southerly direction; the southwesterly zone was defined as described earlier (Figure 4). The temperature was compared between the southwesterly and southerly zones by averaging the maximum temperature for all days that the air parcel passed through the respective zone. The odds ratio was then calculated for both the southwesterly and southerly exposure classifications relative to the bounded northerly zone.

4. Results

The box–plots in Figure 5 display the ozone concentrations averaged for the northerly and southwesterly transport directions (defined by the arc and bounded zone methods) for each of the eight NYS regions. The center–line of the box identifies the median ozone concentration, the lower and upper extent of the box represents the 25th and 75th percentile, the upper and lower whiskers represent the 5th and 95th percentiles, and the dashed line represents the 10–year summer average for all eight NYS regions. Regardless of whether the southwesterly direction was defined by the arc or bounded zone method, the mean ozone concentration for the southwesterly direction was significantly higher than the ozone concentration for the northerly direction for all eight regions ($p < 0.0001$ for each region regardless of the method).

Table 1 shows the results of the odds ratio calculations comparing the exposed group with the unexposed group. Table 1 also shows that the odds ratios (including 95% confidence intervals) are statistically significant for Regions 2, 7, and 8 when the exposed and unexposed groups are defined using the arc approach. The odds ratios are also statistically significant for Regions 1, 2, 3, 6, 7, and 8 in comparing the exposed group to the unexposed group using the bounded zone approach.

The minimum, medium and maximum temperatures for the southerly arc approach were similar to the southwesterly zone approach (22 °C, 26 °C and 29 °C versus 19 °C, 24 °C and 29 °C, respectively). The odds ratio, however, is lowest for the southerly zone as compared to the odds ratio calculated for the southwesterly zone (Figure 6).

5. Discussion

In this study, the population for both the exposed and unexposed groups is the same because the exposure is defined by day. Therefore, several variables that may confound or modify the effect of the exposure (e.g., socioeconomic status, gender, age, day–of–week, holidays) are controlled by the design of the analysis. The study does not, however, investigate the potential time lag between the exposure and the health endpoint. This weakness in the study design is somewhat compensated for, though, because the time scale for synoptic weather changes is usually 3–5 days (Rao et al., 1997). Since the unadjusted odds ratio is a measure of prevalence (number of respiratory–related hospital admissions for the entire study time period), the lag effect is partially incorporated into the study design because of the length of time that the exposure exists. Long–term trends (e.g., climate change), however, may be a confounder (related to both the exposure of interest and the health endpoint), but it is unlikely that the long–term trend signal embedded in the days of high exposure would be different from the trend embedded in the days of low exposure. Local pollution (versus pollution transported over relatively long distances) may also influence the results of the study, especially when using the arc approach. While the bounded zone approach targets transported pollution more effectively than the arc method, local pollution may still be associated with wind flow from a particular direction. However, the likelihood of this exposure misclassification occurring across all eight NYS regions is unlikely.

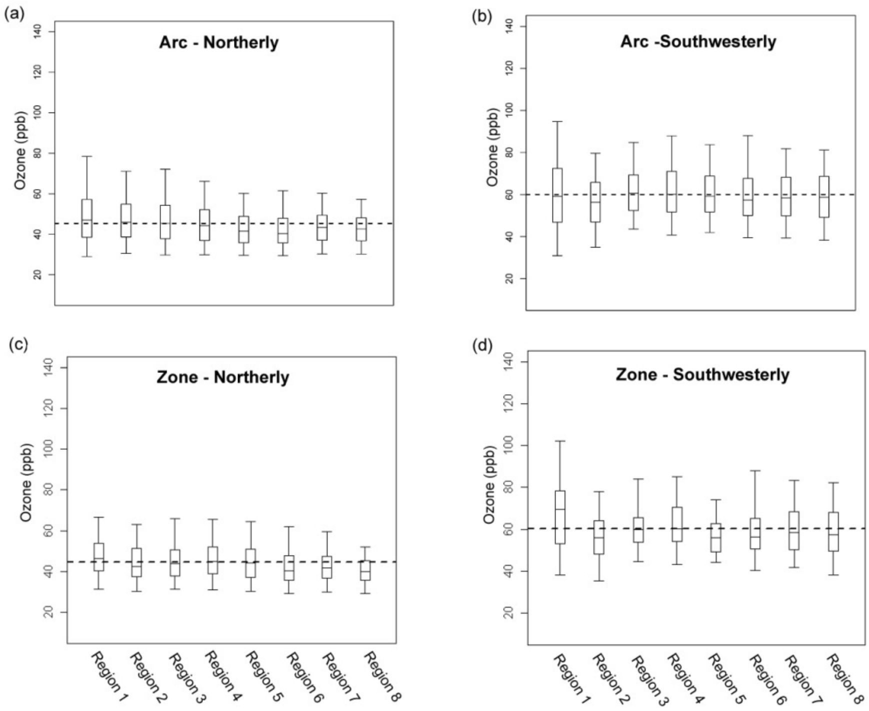

Figure 5. *Boxplots displaying the daily maximum 8-h ozone concentrations for **(a)** northerly direction defined using the arc method; **(b)** southwesterly direction defined using the arc method; **(c)** northerly direction defined using the bounded zone method; and **(d)** southwesterly direction defined using the bounded zone method.*

Table 1. *Odds ratio calculations resulting from the arc and bounded methods of determining exposure*

Region	Odds Ratio (95% Confidence Intervals)	Number of Days (Exposed)	Number of Hospital Admissions (Exposed)	Number of Days (Unexposed)	Number of Hospital Admissions (Unexposed)	Total Population
			Arc Approach			
1	1.02 (0.98 to 1.07)	228	4 070	581	10 165	2 753 913
2	1.04 (1.02 to 1.06)	197	17 660	599	51 691	9 218 490
3	1.05 (0.97 to 1.13)	199	1 407	601	4 050	968 977
4	1.02 (0.96 to 1.08)	262	2 423	567	5 151	1 102 987
5	1.08 (0.98 to 1.18)	308	914	508	1 398	441 863
6	1.05 (0.99 to 1.12)	291	1 969	541	3 480	1 063 223
7	1.04 (1.00 to 1.09)	297	4 031	532	6 925	1 885 223
8	1.07 (1.02 to 1.13)	318	3 399	504	5 018	1 541 781
			Bounded Zone Approach			
1	1.09 (1.02 to 1.17)	100	1 836	172	2 889	2 753 913
2	1.06 (1.03 to 1.09)	114	10 374	161	13 825	9 218 490
3	1.16 (1.04 to 1.29)	92	701	196	1 287	968 977
4	1.06 (0.98 to 1.16)	114	1 098	282	2 555	1 102 987
5	1.13 (0.94 to 1.36)	76	238	369	1 022	441 863
6	1.13 (1.03 to 1.24)	130	937	303	1 932	1 063 223
7	1.08 (1.02 to 1.14)	173	2 427	202	2 624	1 885 223
8	1.10 (1.03 to 1.16)	211	2 312	138	1 378	1 541 781

The analysis of the ozone concentrations associated with each arc or bounded zone direction supports that air parcels originating in the Midwest are associated with higher ozone concentration levels. For some regions, ozone concentrations were also significantly different between air parcels originating from the south or west as compared to air parcels originating from the north. However, air parcels originating from the southwest were significantly different for all eight NYS regions, regardless of the method used. Thus, the use of the southwesterly and northerly air parcel origin classification to define the exposed and unexposed groups for calculating the odds ratio is substantiated by this analysis because the ozone concentrations are significantly higher for the exposed group as compared to the unexposed group.

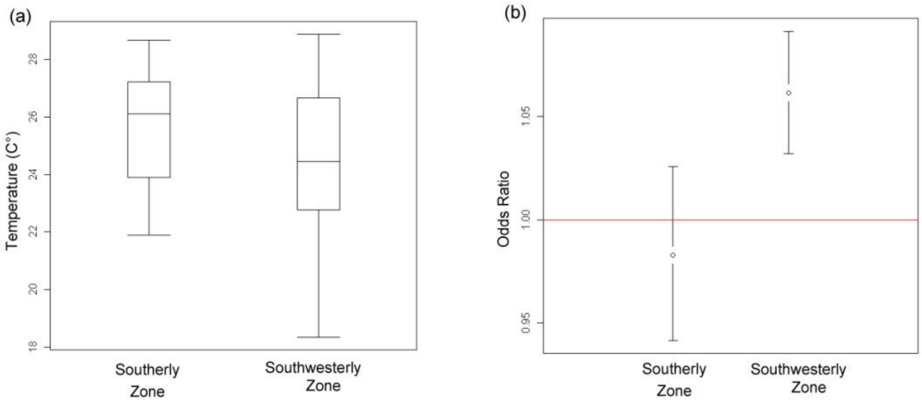

Figure 6. *Panel **(a)** boxplots show the interquartile range and 5th and 95th percentiles for maximum temperature in region 2 on days when air transport is from the south and the southwest (as defined by the bounded zone method). Panel **(b)** shows the odds ratio calculations for these two exposure definitions.*

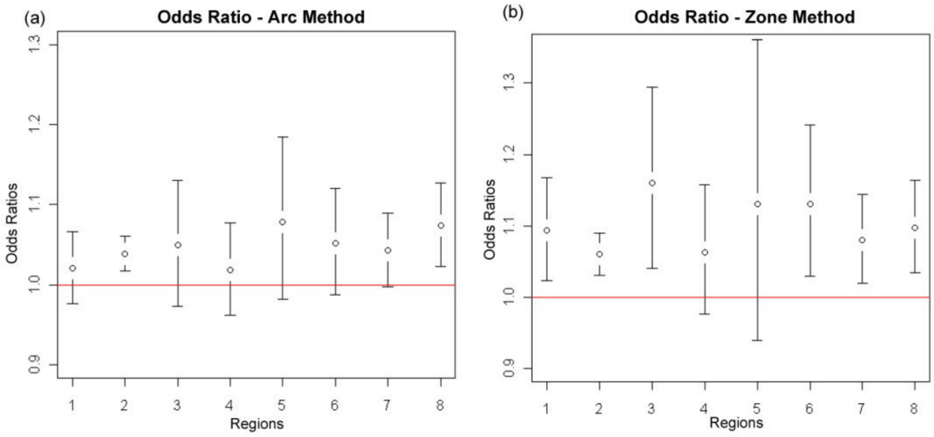

Figure 7. *Odds ratios with 95% confidence intervals for panel **(a)** arc approach and panel **(b)** bounded zone approach.*

The unadjusted odds ratio calculation for the arc approach indicates that respiratory–related hospital admissions were elevated on southwesterly wind flow days for all regions over the entire study time period, with significant associations for regions 2, 7, and 8 (Figure 7). The number of exposed days was less for the bounded zone approach than for the arc approach because there are fewer days that the air parcel passes through the Midwest zone as compared to originating from the southwesterly direction. Despite the wider confidence intervals (particularly for Region 5), the odds ratios increased for all regions when using the bounded zone approach to define exposure as compared to the arc approach, and became significant for regions 1, 3, and 6 in addition to regions 2, 7, and 8 (Figure 7). These results indicate that respiratory health is impacted in regions 1, 2, 3, 6, 7, and 8 when air parcels are transported from the Midwest zone into NYS.

Despite the similarity in the minimum, medium and maximum temperatures for the southwesterly and southerly zones, the odds ratio calculations revealed a lower risk for exposure to air parcels originating from the south versus air parcels originating from the southwest (Figure 6). This analysis indicates that there is more influencing the odds ratios calculations than temperature alone, providing evidence that polluted air parcels transported from the Midwest zone contribute to the incidence of respiratory–related hospital admissions in NYS.

6. Summary

Focusing on NYS and its inhabitants, this study applied two successive methodologies (arc and bounded zone) to classify polluted air transported from the Midwest and relatively clean air transported from the North for ten consecutive summers between 1997 and 2006. Daily averaged ambient ozone measurements were used to validate the classification methods, and the classes were used to define exposed and unexposed groups for purposes of calculating the odds of respiratory–related hospital admissions occurring in the respective groups.

The study results revealed spatial differences in associations between the origin of the air parcel and daily maximum 8–h ozone concentrations. However, the mean ozone concentration and the direction of the air parcel origin were consistently and significantly different for all eight regions for the southwesterly versus northerly directions. The bounded zone methodology was used to isolate transported air from the Midwest, and using this method the unadjusted odds ratio indicated positive associations between respiratory–related hospital admissions and exposure to polluted air parcels for all regions. The results were significant (lower extent of confidence interval > 1.0) for regions 1, 2, 3, 6, 7, and 8. These results indicate that exposure to air parcels transported from the Midwest into NYS (as compared to air parcels that originate in the North) result in excessive risk for increased respiratory–related hospital admissions over the entire 10–year study time period for regions 1, 2, 3, 6, 7, and 8. These findings are consistent with the southwesterly transport patterns seen in NYS. The temperature analysis supported that temperature alone does not explain this increased association for region 2 during the time period studied.

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